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KALMAN FILTERING FOR SPACE-TIME CODED TRANSMISSIONS OVER FREQUENCY-SELECTIVE RAYLEIGH FADING CHANNELS

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ABSTRACT

The problem of multichannel estimation for space-time coded transmissions over frequency-selective Rayleigh fading channels is addressed. Under fast fading conditions, receivers employing Kalman filtering and moderate complexity equalization schemes are proposed for both space-time block codes (STBCs) and space-time trellis codes (STTCs). Simulation results of the proposed receivers demonstrate good performance.

Keywords: *Equalizers, Kalman filters, Rayleigh fading channels, space-time codes.*

1. INTRODUCTION

Space-time coding is an attractive coding technique that employs multiple transmit antennas and single or multiple receive antennas for mitigating fading effects. It offers power gain without sacrificing bandwidth. Especially when the channel is fast Rayleigh fading, multichannel estimation is necessary for space-time communications. Channel tracking algorithms with constant adaptation gains, such as least mean-squares (LMS) and recursive least-squares (RLS) algorithms, are sensitive to noise and this leads to error floor [1]. On the other hand, since Kalman filter takes the advantage of time evaluation model of the channel, it can successfully track fast channel variations.

Kalman filtering based multichannel estimation for space-time coded signals over flat Rayleigh fading channels was presented in [2, 3]. In this letter, we consider the frequency-selective Rayleigh fading case. For space-time block codes (STBCs), the block level decision-feedback equalizer (DFE) is revised for the fast fading case and a receiver based on Kalman filtering is presented. For space-time trellis codes (STTCs), a receiver with per-survivor Kalman filtering and delayed decision feedback sequence estimation (DDFSE) is presented. It is confirmed by simulation results that the presented receivers achieve good performance under fast fading conditions.

2. KALMAN FILTERING

We consider a space-time coded system with two transmit and n_R receive antennas. At nth coding instant, the received signal at the jth antenna can be written as,

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$$r_j[n] = \sum_{i=1}^{2}\sum_{l=0}^{L} h_{ij,l}[n]\, s_i[n-l] + w_j[n],$$
$$j = 1, 2 \ldots, n_R \qquad (1)$$

where L is the channel memory, $h_{ij,l}[n]$ denotes the fading coefficient between ith transmit antenna and jth receive antenna. $s_i[n]$ is the transmitted signal from the ith transmit antenna and $w_j[n]$ represents the white Gaussian noise. Kalman filter can be used as a multichannel estimator if dynamical modeling of the multichannel is possible. Fortunately, the multichannel variations can be approximated by the following autoregressive (AR) model,

$$\mathbf{H}[n] = \mathbf{A}\mathbf{H}[n-1] + \mathbf{U}[n] \qquad (2)$$

where

$$\mathbf{H}[n] = \left[\mathbf{H}_1[n]\ \ \mathbf{H}_2[n] \cdots \mathbf{H}_{n_R}[n]\right]$$

$$\mathbf{H}_j[n] = \left[\mathbf{h}_j[n]\ \ \mathbf{h}_j[n-1] \cdots \mathbf{h}_j[n-p+1]\right]^{\mathrm{T}} \qquad (3)$$

$$\mathbf{h}_j[n] = \left[h_{1j,0}[n]\ \ h_{2j,0}[n]\ \ h_{1j,1}[n]\ \ h_{2j,1}[n] \cdots h_{1j,L}[n]\ \ h_{2j,L}[n]\right]$$

Here, $\mathbf{A}$ is the known $2p(L + 1)$ x $2p(L + 1)$ state transition matrix and p is the AR model order. $\mathbf{U}[n]$ is the noise matrix of the AR model whose non-zero entries are independent and identically distributed (i.i.d.) zero-mean Gaussian samples. Using the notation of (2), (1) can be rewritten as

$$\mathbf{r}[n] = \mathbf{S}[n]\mathbf{H}[n] + \mathbf{w}[n] \qquad (4)$$

where

$$\mathbf{r}[n] = \left[r_1[n]\ \ r_2[n] \cdots r_{n_R}[n]\right] \qquad (5)$$

and

$$\mathbf{S}[n] = \left[\mathbf{s}[n]\quad \mathbf{0}_{1 \times 2(p-1)(L+1)}\right]$$

$$\mathbf{s}[n] = \left[s_1[n]\ \ s_2[n]\ \ s_1[n-1]\ \ s_2[n-1] \cdots s_1[n-L]\ \ s_2[n-L]\right] \qquad (6)$$

$\mathbf{0}_{1 \times 2(p-1)(L+1)}$ is the all-zeros matrix of size 1 x $2(p - 1)(L + 1)$ and $\mathbf{w}[n]$ is the noise vector. Based on the previous multichannel estimates and the previously detected symbols, $\mathbf{H}[n]$ can be estimated using the Kalman filter recursions given in [3].

3. JOINT KALMAN FILTERING AND EQUALIZATION FOR STBCS

First we develop a decision-feedback equalization scheme for fast fading, which jointly operates with Kalman filtering. For STBCs, finite-length block DFE with feedforward filter order N_f, feedback filter order N_b, and decision delay Δ was proposed in [4] where the space-time block encoder and the fading channel were considered as an equivalent overall channel with memory $\overline{L}$. However, the approach in [4] was developed for slow fading channels. In this work, we construct the multichannel convolution matrix for the fast fading case. In order to compute the optimum minimum-mean-square-error (MMSE) DFE coefficients, the autocorrelation of the MMSE DFE error vector is derived and constrained optimization problem is solved using the method given in [5].

For Alamouti's STBC [6], the proposed block (2 symbols) level joint multichannel estimation and equalization procedure with Kalman filtering and DFE with optimum settings $N_{b,opt} = \overline{L}$ and $\Delta_{opt} = 0$, which are valid under the assumption of white input and noise, can be summarized;

i. Obtain $\mathbf{H}[n_0 \mid n_0 - 1]$ from initial training.
ii. By setting $\mathbf{H}[n_0 + 2N_f - 1 \mid n_0 - 1] = \mathbf{A}\mathbf{H}[n_0 + 2N_f - 2 \mid n_0 - 1] = \ldots = \mathbf{A}^{2N_f - 1}\mathbf{H}[n_0 \mid n_0 - 1]$ perform temporary equalization of space-time block coded signals. Obtain hard decisions for $\mathbf{S}[n_0]$ from the encoding rule.
iii. Calculate $\mathbf{H}[n_0 + 1 \mid n_0]$ using Kalman filter.
iv. Perform final equalization of space-time block coded signals by setting $\mathbf{H}[n_0 + 2N_f - 1 \mid n_0] = \mathbf{A}\mathbf{H}[n_0 + 2N_f - 2 \mid n_0] = \ldots = \mathbf{A}^{2N_f - 2}\mathbf{H}[n_0 + 1 \mid n_0]$. Obtain hard decisions for $\mathbf{S}[n_0 + 1]$ from the encoding rule.
v. Run Kalman filter to calculate $\mathbf{H}[n_0 + 2 \mid n_0 + 1]$ for the next recursions.

Due to the channel prediction operations performed in steps (ii) and (iv), increasing the value of N_f much degrades the performance. Hence, the value of N_f must be optimized via simulations. Note that the proposed procedure can successfully be extended to other STBCs.

4. JOINT KALMAN FILTERING AND EQUALIZATION FOR STTCS

The proposed symbol level joint multichannel estimation and equalization procedure for STTCs based on DDFSE [7] and per-survivor Kalman filtering has three steps.

i. From initial training obtain $\mathbf{H}^{(k)}[n_0 \mid n_0 - 1]$ for each kth state.
ii. For each state, calculate the path metrics where each transition metric is calculated using the multichannel estimate based on the previous state of the transition, $\mathbf{H}^{(k)}[n_0 \mid n_0 - 1]$. Store the path with the lowest metric and construct $\mathbf{S}^{(k)}[n_0]$ using the survivor path.
iii. For each state, run Kalman filter based on the survivor path (and the corresponding previous multichannel estimate) to calculate $\mathbf{H}^{(k)}[n_0 + 1 \mid n_0]$ which is required for next recursions.

5. SIMULATION RESULTS

Simulation results examine 4-PSK modulation over a frequency-selective Rayleigh fading channel with $L = 1$, which approximates the typical urban conditions. Doppler rate of the channel is 0.01. It is assumed that the antenna spacings are placed depart from each other which results in mutually uncorrelated fading amplitudes. Because of the U-shaped spectrum of the fading process, we choose $p = 2$. Additionally, it is confirmed by simulations that increasing p will not significantly improve the performance. To avoid divergence in the Kalman filtering pilot symbols must be inserted. The best training strategy is inserting pilot symbols with length of $p = 2$ which are assumed to provide perfect initial channel estimates. In all simulations the bandwidth efficiency loss due to training is 10 %.

Fig. 1 shows the bit error rate (BER) performance of the proposed receiver for Alamouti's STBC with two transmit and one receive antennas. The number of feedforward taps is selected as four which is the optimum value for the specified simulation parameters. We observe that the proposed receiver for Alamouti's STBC offers good error rate performance even when the channel is frequency-selective Rayleigh fading with a high Doppler rate.

Fig. 2 plots the performance of the proposed receiver for 4-state 4-PSK STTC [8] with the same number of transmit and receive antennas. Since most of the channel energy is concentrated on the first tap, 4-state DDFSE is employed without prefiltering. It is shown in Fig. 2 that the multichannel estimation error is small.

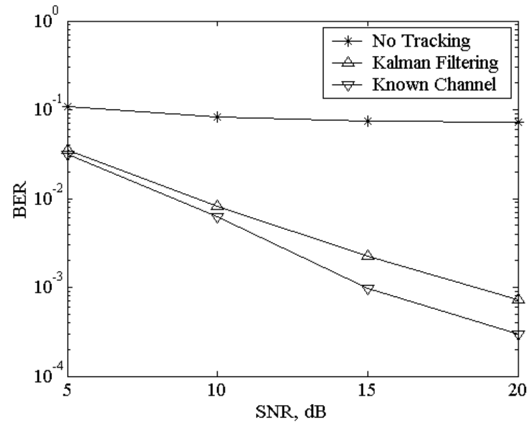

Figure 1. *Performance of the proposed receiver for Alamouti's STBC with one receive antenna over frequency-selective Rayleigh fading channel.*

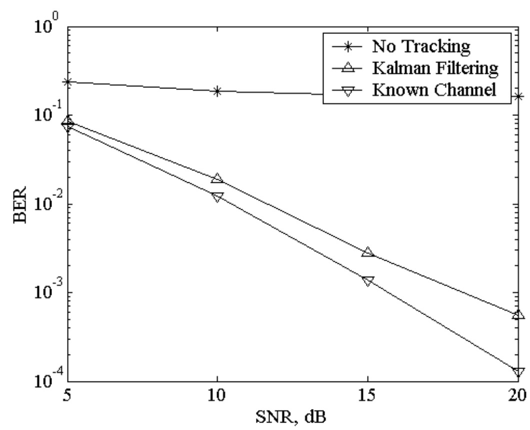

Figure 2. *Performance of the proposed receiver for 4-state STTC with one receive antenna over frequency-selective Rayleigh fading channel.*

6. CONCLUSIONS

In this letter, new receivers with Kalman filtering and moderate complexity equalization schemes are presented for both STBCs and STTCs over frequency-selective Rayleigh fading channels. Discussions on pilot symbol insertion and equalizer length are made. It is confirmed by simulations that the presented receivers achieve good error rate performance even for a high Doppler rate.

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